Advanced Guidance and Control for Hypersonics and Space Access

DRAFT

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Abstract

Advanced guidance and control (AG&C) technologies are critical for meeting safety, reliability, and cost requirements for the next generation of reusable launch vehicle (RLV), whether it is fully rocket-powered or has air-breathing components. This becomes clear upon examining the number of expendable launch vehicle failures in the recent past where AG&C technologies could have saved a RLV with the same failure mode, the additional vehicle problems where this technology applies, and the costs and time associated with mission design with or without all these failure issues. The state-of-the-art in guidance and control technology, as well as in computing technology, is at the point where we can look to the possibility of being able to safely return a RLV in any situation where it can physically be recovered. This paper outlines reasons for AG&C, current technology efforts, and the additional work needed for making this goal a reality. There are a number of approaches to AG&C that have the potential for achieving the desired goals. For some of these methods, we compare the results of tests designed to demonstrate the achievement of the goals. Tests up to now have been focused on rocket-powered vehicles; application to hypersonic air-breathers is planned. We list the test cases used to demonstrate that the desired results are achieved, briefly describe an automated test scoring method, and display results of the tests. Some of the technology components have reached the maturity level where they are ready for application to a new vehicle concept, while others are not as far along in development.

Introduction

Currently-demonstrated guidance and control (G&C) technologies are able to automatically fly a reusable launch vehicle to orbit and back to a safe landing. The Space Shuttle has demonstrated this well over 100 times. The guidance and control for the Shuttle is automated except for the approach and landing phase[1,2,3]. Although the astronauts fly the Shuttle during the final phase of flight, an automated system is available[4]. The Shuttle also has the capability to successfully abort for a number of situations where (single or multiple) main engines are shut down during flight[5]. Planning for each abort situation (time of engine loss, number of engines lost) requires a significant amount of ground analysis, as would planning for any other failure scenarios, or for new missions.

Goals for future reusable launch vehicles include significant improvements to vehicle reliability, safety, and cost. Use of AG&C technologies will help make these goals a reality. For defense applications, using more adaptable algorithms will allow faster mission planning.

Safety, Reliability, and Cost Improvements from Advanced Guidance and Control

AG&C technologies can offer the possibility of a safe return under a number of scenarios where it either would not otherwise be available or would require prohibitive amounts of ground analysis to plan each scenario. Among these are:

•Abort to landing site with no change in vehicle dynamics
•Single engine out
•Single engine throttle back
•Single engine throttle back followed by same engine out
•Multiple engines out at same time
•Multiple engines out at different times
•For some reason, vehicle performance is off. Could be thrust deficiency, a component that was supposed to jettison but didn't, or something else
•Vehicle performance is off but current performance looks okay

•Aerosurface frozen at a fixed angle (during entry)
•Aerosurface trails in the breeze (during entry)
•One of the above aerosurface problems is noticed during ascent
•Aerosurface effectiveness not as expected (6DOF increments--entry)
•Aero coefficients not as expected (lift and drag, entry)
•Thrust vector control failure, engine not shut down yet
•Reaction Control System (RCS) failure combination
•Vibration mode is different frequency/amplitude than expected
•Loads on some part of the vehicle are approaching limits (cause unknown)
•Oscillatory behavior in vehicle attitude has been detected
•A component is injured and G&C is asked to 'favor' it
•A resource (e.g. hydraulic fluid or some type of fuel) is being consumed too fast or is leaking during ascent; MECO will be early; only option is to abort
•Abort from orbit to landing ASAP
•Integrated Vehicle Health Management (IVHM) sensor failures means IVHM will not supply certain aerosurface health data (G&C is informed that the sensor is unavailable)
•Same but G&C is not informed that the sensor is off-line
•Slosh modes and amplitudes are not what was expected.
•Abort commanded by ground or crew; some flight mechanics problems may already have occurred.
•IVHM tells us something has failed, but there is a way to evaluate whether to believe the sensor data
•Additional modes for hypersonic airbreathing vehicles: unstarts, flameouts, flowpath asymmetries, undesirable module interactions, etc.

This extensive list makes it clear that AG&C technology can have a big impact. It is reasonable to have the goal of returning the vehicle safely in any situation where it can physically be returned safely. This means that the on-board capability would accommodate any situation where the vehicle is still controllable.

There are many examples of expendable vehicles that have failed in the recent past where AG&C technologies would address the same failure mode had it occurred in a RLV. Table 1 lists failures since 1990, to U.S., European, Japanese, and Russian launchers (that are involved with U.S. companies), where AG&C technologies would address the failure mode had it occurred in a RLV. This represents 42% of all launch vehicle failures for these vehicles in this time period. The cross-cutting benefit of advanced G&C is fairly unique (IVHM is related and is also cross-cutting) and is not available in most technology areas where the new technology applies to a particular component only (such as part of an engine, an actuator, a power supply, etc.). Note also that there are many additional failure modes that AG&C addresses in a RLV that are not part of an expendable vehicle (such as aerosurface failure modes).

Advanced technologies will automatically accommodate changes in vehicle models and failures without analysis to adapt to each case. They will significantly reduce the cycle time for guidance and control during vehicle design, since the algorithms will be much more adaptable to changes in vehicle models and missions without significant effort expended. Finally, they will significantly reduce the analysis required for new missions during vehicle operations, for the same reason. All these improvements contribute to reduced cost and more rapid mission planning.

Table 1. Some Launch Failures (since 1990) that advanced guidance and control would address if the failure occurred in a RLV (U.S., European, and Japanese launchers, Zenit/Proton included due to Boeing/Lockheed Martin programs using those vehicles). Most of these failures can be found in Ref. 6. Some of the specific causes reside in a database compiled at NASA Marshall Space Flight Center.

Date	**Launch Vehicle**	**Payload**	**Reason for Failure**	**RLV Action**
7/17/91	Pegasus	Microsat 1	Pyrotechnic separation failure caused vehicle to steer off course at 1st stage sep., recovered but low orbit	Abort landing trajectory targeted
3/25/93	Atlas I	UHF F1	Inadequately torqued set screw	Abort deorbit and

			caused reduced engine power	landing
5/27/93	Proton	Gorizont 39L	Multiple burn-throughs of combustion chambers, did not reach planned velocity	Abort landing trajectory targeted
1/24/94	Ariane 44LP	Turksat 1, Eutelsat 1	Premature shutdown of 3rd stage due to turbopump bearing overheating	Abort landing trajectory targeted
6/27/94	Pegasus XL	STEP-1	Poor aerodynamic data caused loss of control	Adapt to poor data to maintain control
8/5/95	Delta II	Mugunghwa 1	SRM failed to separate, causing lower than planned orbit	Abort landing trajectory targeted
10/23/95	Conestoga	Meteor Microgravity	Unexpected vibrations caused unnecessary control inputs, exhausting hydraulic fluid	Adapt to unexpected mode
5/20/97	Zenit 2	Kosmos-2344	2nd stage shutdown halfway through burn due to structural failure in engine	Abort landing trajectory targeted
2/21/98	H-II (Japan)	COMETS	Premature shutdown of 2nd stage due to faulty brazing in cooling system	Abort landing trajectory targeted
8/27/98	Delta III	Galaxy 10	Rolling mode not expected to be a problem; exhausted hydraulic fluid	Adapt to unexpected mode
9/9/98	Zenit 2	Globalstar FM5	Computer error caused very premature engine shutdown during 2nd stage	Abort landing trajectory targeted
10/20/98	Ariane 5	Amsat P3D	Roll torque from engine caused premature shutdown	Abort landing trajectory targeted or abort deorbit and landing
5/5/99	Delta III	Orion 3	Engine failure at ignition of upper stage due to poor brazing process in combustion chamber fabrication	Abort landing trajectory targeted
2/10/00	M-5 (Japan)	Astro-E (NASA-Japan)	1st stage corkscrewed through sky; 2nd stage okay	Abort landing trajectory targeted
3/12/00	Zenit 3SL	ICO F-1	2nd stage shutdown early due to software command mistake	Abort landing trajectory targeted
7/12/01	Ariane 5	BSAT2b, Artemis	Loss of thrust from 3rd stage (partial thrust) due to a combustion instability	Abort landing trajectory targeted
9/21/01	Taurus	Orbview, NASA QuikTOMS	Control problem at staging (seized actuator) hurt performance (not enough to reach orbit)	Abort landing trajectory targeted

AG&C Technology Definitions

In order to cover autonomously for all the failure modes described above, we need a hierarchy of algorithms that must all work together:

- Autonomous flight manager (has also been referred to as a mission manager and an autocommander) that pulls data together regarding vehicle performance and flight dynamics, and decides how to react. Use of IVHM inputs along with system identification (described below) and on-board simulation of vehicle performance are probably all required. Some questions for this software include: Do we need to abort? Where should we try to land? What are the new trajectory constraints? Is any control reconfiguration necessary? Does the trajectory/guidance need to back off on commands to accommodate a control problem? A higher-level mission manager than this one might tell GN&C to abort when things are okay dynamically.

- On-board trajectory redesign with constraints. Note this is a very different question (in terms of vehicle dynamics and probably solution method) for powered ascent/abort versus unpowered entry versus the final phases of flight.
- Guidance that adjusts the commands (which include commanded body attitude and possibly throttle setting) to fly the best way possible, accommodating control system limitations. A continuous trajectory redesign could function as a guidance method.
- Control (commands the torques about the various body axes in an effort to fly to the guidance commands) that reacts quickly to failures, and does not require ground-designed gain adjustment for different cases.
- Adaptive control allocation (allocates the torque commands to the various available control effectors, including thrust vector control, aerosurfaces, and reaction control system) to obtain the control needed from the available control effectors, in whatever state they are in.
- System identification to identify the effects of failures on the vehicle dynamics. System or parameter identification is using navigation data, effector commands, and any other available information to determine something about the plant (dynamic behavior of the vehicle). This may be determining the actual behavior of a specific surface, or may be determining the effect on the vehicle from the collective response to whatever is going on (such as a change in the capability to maneuver about a particular axis). The results of system identification must provide useful information to the vehicle guidance and control and must be available quickly to avoid loss of control.

Current Efforts in AG&C Technology as Applied to RLVs

A number of efforts have been underway, in areas that apply to all the technologies required. These efforts were briefly surveyed in a previous paper[7], and include all the parts of an AG&C system and all flight phases. Although testing will ultimately be necessary for all the components of the AG&C system, individually and later fully integrated, only certain parts have been tested so far. This testing has encompassed aspects of ascent/abort trajectory design/guidance, entry trajectory design/guidance, and ascent and entry flight control. The testing used a high-fidelity vehicle simulation to test for the ability of the algorithms to successfully accommodate various failures, dispersions, and mis-modeling[8]. X-33 models were used for the entry guidance and flight control testing, and a generic two-stage RLV model was used for ascent guidance testing.

Testing

The results in this paper continue from work described earlier in reference 8. The methods under examination are listed here for reference:

Ascent/abort trajectory design and guidance: references 9 and 10. Open-loop ascent guidance, followed by linear tangent steering (optimal vacuum guidance) is used for comparison[11].
Entry trajectory design and guidance: references 12-15. The Shuttle-based guidance that was the X-33 baseline[16] is used for comparison, and proportional-integral-derivative (PID; X-33 baseline) control[17] is used when 6 degree-of-freedom simulations are run.
Ascent and entry flight control: references 18-21. A proportional-integral-derivative (PID; X-33 baseline) control is used for comparison[17].

A list of the test cases follows in Table 1. The test environment is a high-fidelity simulation of the X-33 lifting body single stage launch vehicle for the entry guidance and control tests, and a two-stage reusable launch vehicle model for the ascent guidance tests. While hypersonic airbreathing vehicles were not modeled in these tests, tests of airbreathing vehicles are planned for the future. It is expected that control methods that are adaptable to engine failures and aerosurface failures for rocket-powered vehicles should be adaptable to engine off-performance related to hypersonic engine problems. Likewise, trajectory redesign methods for powered ascent flight that retarget landing sites and design trajectories with constraints should be adaptable to situations where engine performance is off on a hypersonic airbreather. Entry trajectory redesign algorithms should be able to design new trajectories (in abort cases, where the engine is no longer providing propulsion) whether the vehicle is rocket-powered or airbreathing. While each algorithm will need some modification to apply to the new type of vehicle, the method should be sufficiently general.

Note that in the flight control tests, the aerosurface failure cases are somewhat arbitrary, but are a mix of cases. Work is in progress to run tests for each surface at each possible failure angle, but this test set-up is not complete yet. The test criteria (used to obtain scores for the performance of the algorithms) used are too extensive to be listed in detail here, and are more fully defined in reference 8. They include aerosurface deflections, engine TVC, control effector duty cycles, body rates and accelerations, structural load indicators, success in meeting engine cutoff conditions, success in meeting desired conditions at the end of the entry phase, reaction control system usage, usage of aerosurfaces, thermal indicators, and control-related attitude limits.

Table 1. Test Series

DOF: Degrees of Freedom; MCD: Monte Carlo Dispersions; PPO: Power Pack Out (Engine Failure, time of failure indicated); Michael (nominal) and Ibex (low energy) are X-33 landing sites; Mich10a1 and 10d1 are X-33 trajectories (10d1 is a higher-energy flight); MECO: main engine cutoff; alpha is angle of attack; Q is dynamic pressure; Q-alpha is dynamic pressure times angle of attack; seed indicates whether a new random number was used to start certain test cases. All environments are for the month of April unless noted. EAFB is Edwards AFB. GRAM is Global Reference Atmosphere Model. ISS is International Space Station; LEO is low Earth orbit. TVC is thrust vector control.

ASCENT GUIDANCE TEST SERIES (All use 2-stage generic reusable launch vehicle models)

Test Number & Description	DOF	No. of Runs
1) Ascent to 28.5-deg orbit, 100 nm circular. #	3	100 MCD
2) Ascent to 51.6-deg orbit, 50x100 nm, in-plane injection.	3	1
3) Same as 2, but this is a rendezvous mission, launched 5 minutes after the in-plane case. *	3	100 MCD
4) Same as 2, but this is a rendezvous mission, launched 5 minutes before the in-plane case. *	3	100 MCD
5) Abort to same orbit as no. 2, with 67% propulsion loss 10 sec prior to main engine cutoff (MECO). Tests ability of guidance to adapt to a problem shortly before MECO. *	3	100 MCD
6) Ascent to same orbit as no. 2, with 50% loss of thrust at the earliest possible time. Up to 500 fps underspeed allowed at MECO, assuming orbital maneuvering system (OMS) will make up the loss.	3	multiple
7) Downrange aborts with 50% thrust loss. Measuring the earliest and latest times where successful abort occurs. Up to 500 fps from OMS. Limits are placed on attitude and load indicators.	3	multiple
8) Abort to launch site with 20% thrust loss starting at launch time, and continuing until the vehicle is no longer able to return. Limits are placed on attitude and load indicators.	3	multiple
9) Same as 8, but run for a case that is 10 sec before the latest possible of these aborts. *	3	100 MCD
10) Same as 8 with 33% thrust loss at max dynamic pressure. Limits are placed on attitude and load indicators.	3	1
11) Same as 8 with no thrust loss.	3	multiple
12) Same as 11 but run for a case that is 20 sec before the latest possible of these aborts. *	3	100 MCD

Wind provided to guidance is mean annual; wind seen in simulation is randomized from GRAM.

* The cases all involve day of launch wind measurement. A smoothed wind profile is available to guidance. Another profile, measured a few hours later, is the wind that the vehicle must fly.

ENTRY GUIDANCE TEST SERIES (All use X-33 vehicle models; 6DOF runs are high fidelity)

Test Number & Description	DOF	# Runs
1) Mich10a1	6	100 MCD
2) Mich10a1, February environment, different random seed	6	200 MCD
3) Mich10d1	6	100 MCD
4) Mich10d1, August environment, different random seed	6	200 MCD
5) Mich10a1, PPO time 50 sec (early abort to Michael)	3	100 MCD
6) Mich10a1, PPO time 60 sec	3	100 MCD
7) Mich10a1, PPO time 112 sec	3	100 MCD
8) Mich10a1, PPO time 40 sec (early to Ibex), different random seed	3	200 MCD
9) Mich10d1, PPO time 38 sec (early to Ibex), different random seed	3	200 MCD
10) Mich10a1, +4 sigma thrust dispersion from ascent	3	1
11) Mich10a1, +6 sigma thrust dispersion from ascent	3	1
12) Mich10a1, -12 sigma thrust dispersion from ascent	3	1
13) 51.6 deg. ISS orbit entry, low crossrange, high peak heat rate limit, input profile to guidance is from	3	100 MCD

this trajectory's design.		
14) 51.6 deg. ISS orbit entry, high right crossrange, high peak heat rate limit, input profile from 13.	3	100 MCD
15) 51.6 deg. ISS orbit entry, high left crossrange, high peak heat rate limit, input profile from 13.	3	100 MCD
16) 51.6 deg. ISS orbit entry, low crossrange, low peak heat rate limit, input profile from this trajectory's design.	3	100 MCD
17) 51.6 deg. ISS orbit entry, high right crossrange, low peak heat rate limit, input profile from 16.	3	100 MCD
18) 51.6 deg. ISS orbit entry, high left crossrange, low peak heat rate limit, input profile from 16.	3	100 MCD
19) 28.5 deg. LEO orbit entry, low crossrange, low peak heat rate limit, input profile from 16.	3	100 MCD
20) 28.5 deg. LEO orbit entry, high right crossrange, low peak heat rate limit, input profile from 16.	3	100 MCD
21) 28.5 deg. LEO orbit entry, high left crossrange, low peak heat rate limit, input profile from 16.	3	100 MCD
22) Mich10a1, aerosurface failure result: angle of attack limited to 5 deg. less that nominal entry value.	3	1
23) Mich10a1, aerosurface failure result: angle of attack and bank rates limited to 2 deg./sec. maximum.	3	1
24) Mich10d1, aerosurface failure: angle of attack limited to 5 deg. less that nominal entry value.	3	1
25) Mich10d1, aerosurface failure: angle of attack limited to 5 deg. less that nominal entry value, and angle of attack and bank rates limited to 2 deg./sec. maximum	3	1
26) Mich10a1, unknown to guidance, first flight aerodynamics mis-modeling: aerodynamic lift coef. 20% less than vehicle database model.	3	1
27) Mich10a1, unknown to guidance, first flight aerodynamics mis-modeling: aerodynamic lift coef. 20% more than vehicle database model.	3	1
28) Mich10a1, unknown to guidance, first flight aerodynamics mis-modeling: aerodynamic lift coef. 20% less and aerodynamic drag is 20% more than vehicle database model.	3	1

FLIGHT CONTROL TEST SERIES (All use high-fidelity X-33 vehicle models)

Test Number & Description	DOF	# Runs
1) Mich10a1	6	1
2) Mich10d1	6	1
3) Mich10a1, PPO time 36 sec (early to Ibex)	6	1
4) Mich10d1, PPO time 50 sec (early to Michael)	6	1
5) TVC command bias on Engine A: Roll/Pitch TVC commands +0.5%	6	1
6) TVC command bias on Engine B: Roll/Pitch TVC commands -1.0%	6	1
7) TVC command bias on Yaw: TVC commands +1.0%	6	1
8) +3 sigma Fz, My on Engine A, -3 sigma Fz, My on Engine B	6	1
9) Right inboard elevon fails to +10 deg. 50 seconds into flight for 30 seconds.	6	1
10) Left outboard elevon fails to –15 deg. 275 seconds into flight for 45 seconds.	6	1
11) Right flap fails to +2 deg. 150 seconds into flight for 20 seconds.	6	1
12) Right flap fails to +2 deg. 300 seconds into flight for 20 seconds.	6	1
13) Right rudder fails to -30 deg. 30 seconds into flight for remainder of flight.	6	1
14) Left inboard elevon fails to null 35 seconds into flight for remainder of flight.	6	1
15) Right outboard elevon fails to null 250 seconds into flight for remainder of flight.	6	1
16) Right flap fails to null at 20 seconds into flight for remainder of flight.	6	1
17) Left flap fails to null at 215 seconds into flight for remainder of flight.	6	1
18) Right outboard elevon jams 58 seconds into flight for remainder of flight.	6	1
19) Left inboard elevon jams 208 seconds into flight for remainder of flight.	6	1
20) Right flap jams 170 seconds into flight for remainder of flight.	6	1
21) Left flap jams 280 seconds into flight for remainder of flight.	6	1
22) Right inboard elevon fails to "trailing in the breeze" (coefficients set to zero)	6	1
23) Left outboard elevon fails to "trailing in the breeze" (coefficients set to zero)	6	1
24) Right flap fails to "trailing in the breeze" (coefficients set to zero)	6	1
25) Right rudder fails to "trailing in the breeze" (coefficients set to zero)	6	1
26) Fail RCS jets 1&10 at MECO (loss of pure yaw capability)	6	1
27) Fail RCS jets 5&9 at MECO (loss of pure yaw capability)	6	1
28) Fail RCS jet 4 at MECO (loss of yawroll capability)	6	1
29) Fail RCS jet 8 at MECO (loss of yawroll capability)	6	1
30) +3-sigma Cm, +3-sigma C_L, + 3-sigma C_D (pitch moment, lift, and drag coefficients)	6	1
31) –4-sigma Cm, -4-sigma C_L, -4-sigma C_D	6	1
32) –3-sigma CY, -3-sigma Cl, -3-sigma Cn (side force, roll moment, and yaw moment coefficients)	6	1
33) –3-sigma Cm (body flap), +3-sigma CY,Cl,Cn (body flap).	6	1
34) +3 sigma CY, Cl, Cn (elevons)	6	1
35) +4 sigma jet effect increments on control surface effectiveness	6	1

36) +3 sigma adverse yaw moment increments on elevons & body flaps	6	1
37) Mich10a1	6	100 MCD
38) Mich10a1, February environment, different random seed	6	200 MCD
39) Mich10d1	6	100 MCD
40) Mich10d1, August environment, different random seed	6	200 MCD
41) Mich10a1, PPO time 60 sec	6	100 MCD
42) Mich10a1, PPO time 112 sec	6	100 MCD
43) Mich10a1, PPO time 40 sec, different random seed	6	200 MCD
44) Mich10d1, PPO time 38 sec, different random seed	6	200 MCD
45) Mich10a1 with flex filter in attitude and rate error loops	6	100 MCD
46) Mich10d1 with flex filter in attitude and rate error loops	6	100 MCD

Automated Scoring

Tests are numerically scored, and then each test is weighted, with the scores added, so that the algorithms have a final numerical score. Normalization results in a perfect score being given a value of 1.0. For each parameter to be tested, there is a weight, and these multiply that parameter's score and add into the total. Single tests (not Monte Carlo dispersions) are scored as in this example:

Normal acceleration: 0-3.5g, 1.0-2.5g means the score is 1.0 for normal acceleration magnitudes below 2.5, 0.0 for values above 3.5, and linearly varying in between the two limit values. The parameter score is multiplied by the weight for that parameter (normal acceleration) and added into the total score for that test.

For Monte Carlo dispersion tests, the overall score is the average of the individual scores. A final criteria used for the entry guidance and flight control tests regards accuracy in reaching the TAEM targets. If the range, altitude, and heading angles are not sufficiently controlled in order to be able to land successfully, the test was considered a failure (score of 0) even if other criteria were met. Typical values used for the required accuracy at hitting the TAEM condition were 7 nm, 7000 ft, and 10 deg, respectively. If more than 10% of Monte Carlo cases fail to meet these TAEM conditions, then the entire Monte Carlo run is given a score of 0.0.

Results

Results of the tests are shown in the following figures. Tests results are shown at their current state of completion. The entry guidance tests are complete, but the flight control tests are still continuing as improvements are made and the ascent guidance tests are incomplete and preliminary.

Figure 1. Ascent Guidance Test Scores

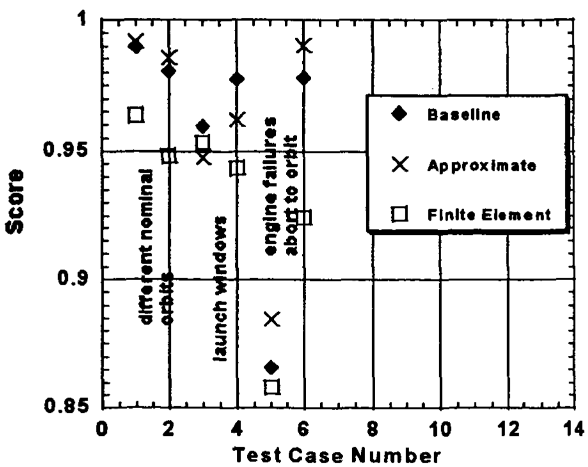
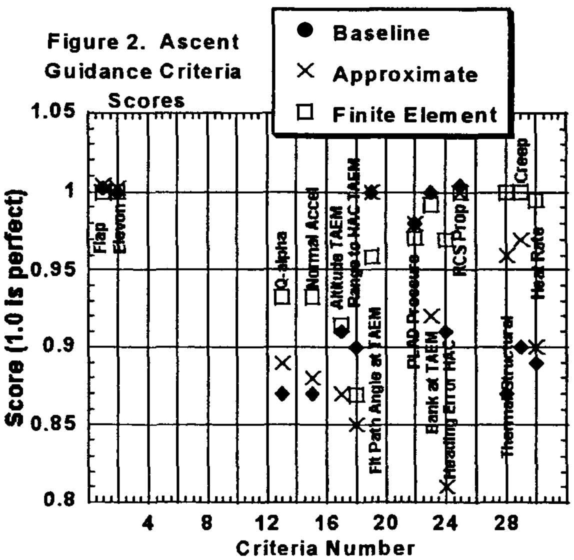


Figure 2. Ascent Guidance Criteria Scores



Note the above figures will be replaced with the actual results as they are available (prior to submission of the final manuscript).

Figure 1 shows the performance for the ascent guidance test cases. The results are preliminary. The algorithms are not yet ready to face the tests for downrange and return-to-launch-site aborts. The real value of the new approaches should be for these types of aborts, rather than in the flight-to-orbit cases that have been scored so far. As previous research has shown, closed-loop optimal guidance flown from the ground up is not significantly better than using an open-loop profile that is biased to a wind profile measured shortly before launch, and followed by vacuum closed-loop guidance (as in the baseline approach) [22]. Figure 2 shows the results for the various criteria.

Figure 3 shows the results of the entry guidance tests. A score of 0.0 means that the algorithm failed the test. If more than one algorithm failed the test, a slightly negative score is used so that the reader is able to see the scores in the figure. The X-33 baseline guidance is used for tests 1-12 only. It is clear that it does quite poorly as compared to the other algorithms. The poor performance of the baseline guidance is due to its relatively poor results in achieving the target end conditions. This can be explained by understanding that the time available on the sub-orbital trajectories is short compared to Shuttle entries; the trajectory maneuvers are more sporty than the Shuttle profile; and the guidance must also remove the dispersions that were introduced during the ascent. Two algorithms passed all the tests: the quasi-equilibrium glide and the drag-energy 3D approaches. Based on this result, we believe these algorithms are ready to be applied to other vehicle models and seriously considered for application to future flight.

Figure 3. Entry Guidance Test Scores

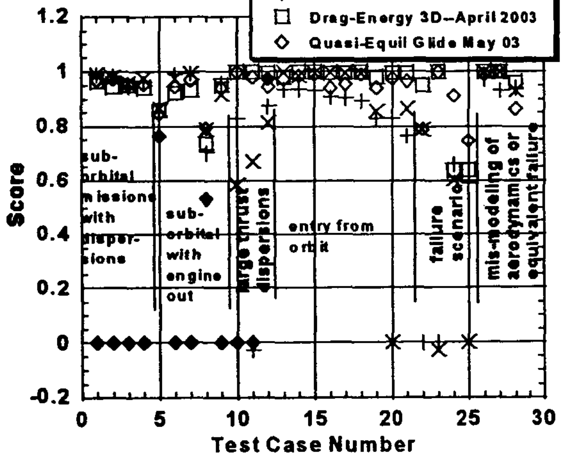
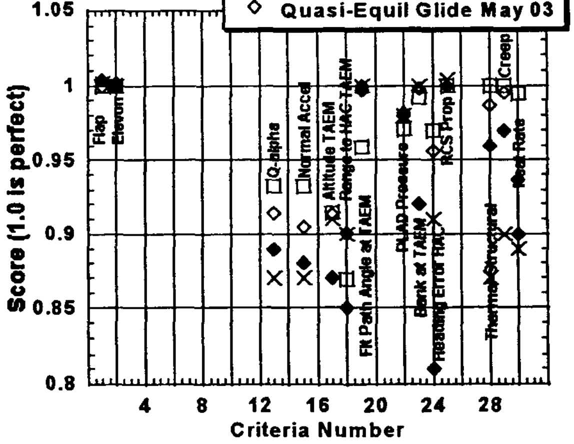


Figure 4. Entry Guidance Criteria Scores



The criteria graph (Fig. 4) shows the performance on the various criteria for each algorithm. The performance is shown only for those tests that did not fail (did not score a zero on the test cases graph). This way, the reader will see information on how the method performed for the various criteria. The number of successful tests for each algorithm can be determined from the test cases graph. Since the baseline passed only one test, its criteria numbers are not meaningful and are left out of the figure.

Figure 5.
Flight Control Test Scores for August New Criteria Weights

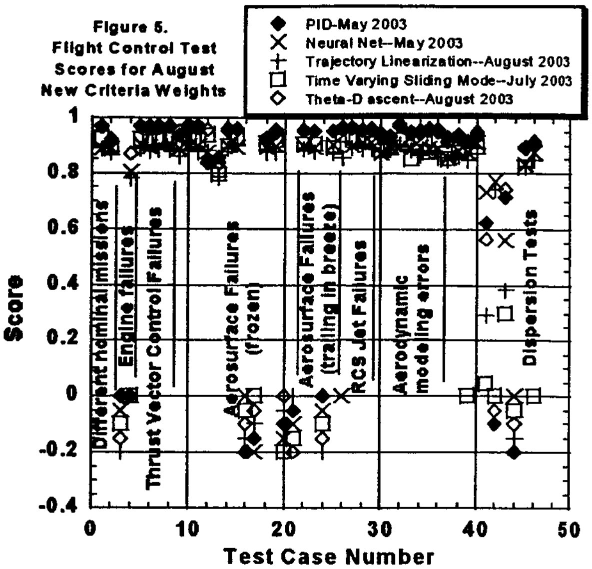


Figure 6.
Ascent Criteria Scores
August 2003

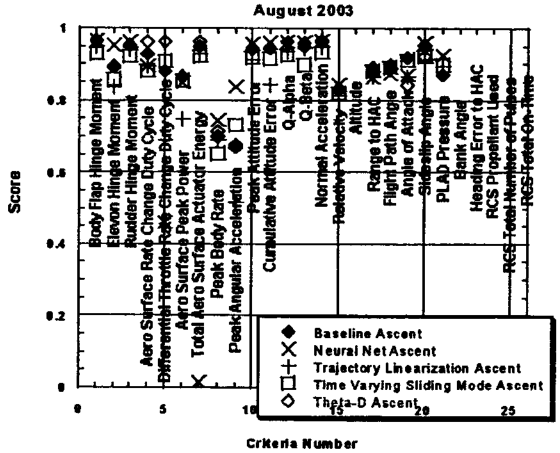
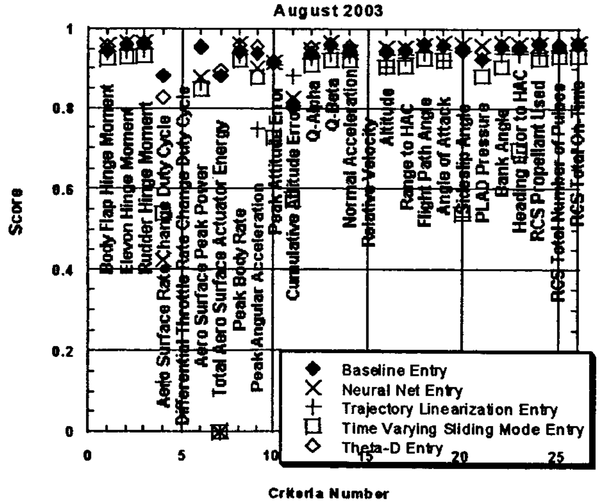


Figure 5 shows the results of control system testing. Currently the Theta-D controller flying ascent with the baseline controller flying entry scores the highest. Several methods have similar results. It is expected that continued testing will yield improvements in the scores. Figures 6 and 7 show the criteria scoring for the control system tests.

Figure 7.
Entry Criteria Scores
August 2003



Summary

This paper describes advanced guidance and control (AG&C) concepts and discusses the safety and cost benefits that can be expected from these technologies. The ability to adapt to a wide range of vehicle failure modes is a particularly compelling argument. Cost savings and rapid mission planning are also enabled through this technology.

The paper gives the results of testing of AG&C methods for application to future reusable launch vehicles, for ascent and entry guidance and flight control. Entry trajectory design and guidance methods exist that are ready for application to new vehicles. Flight control work is continuing and is showing promising results. Ascent trajectory design and guidance work is progressing. Testing for the other flight phases, and for the other components of AG&C, has not been started yet.

Follow-on work is planned to continue this effort and to integrate the various algorithms into a single AG&C architecture. This work is currently funded at a low level, and progress is continuing.

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